USING EXPERIMENTAL TEST DATA IN THE ANALYSIS OF LAMINATED STRUCTURES

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SUMMARY

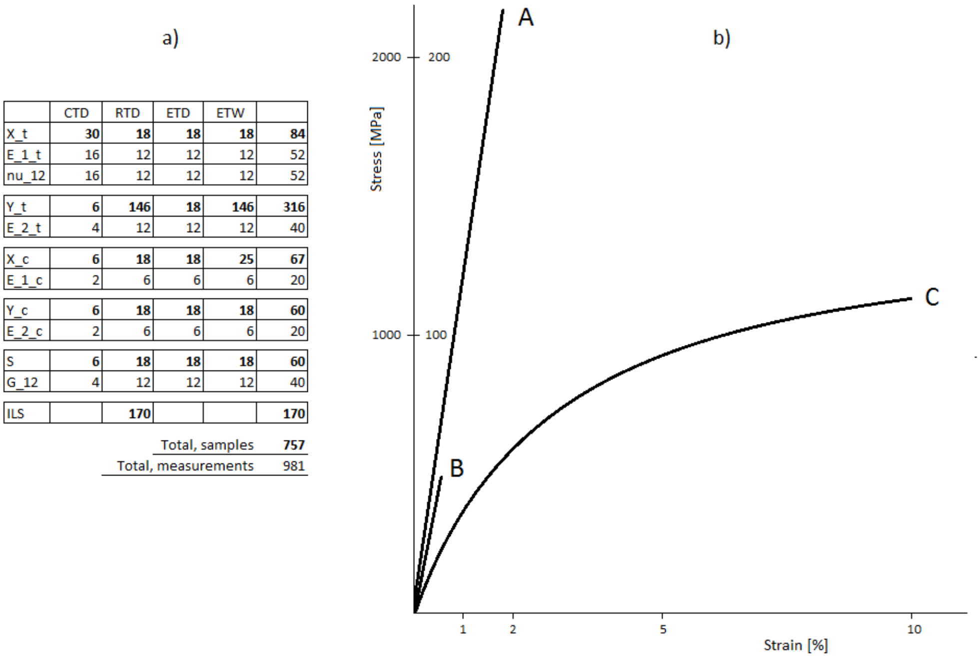
Composite material systems have relatively large variation in their measured properties. A typical approach in engineering problems is deterministic, however. Material stiffness and strength, for example, are described with single values in linear-elastic analyses. Physical dimensions of the material, structural and environmental conditions in the laminate or uncertainties in material properties, for instance, require that several discrete definitions are needed for the material specification.

This paper presents how the experimental test data for Toray T700 UD epoxy UD tape prepared by NIAR (National Institute for Aviation Research) has been translated to a material database format that can be used in the FEA of laminated structures. Also, it is described how the statistical test data can be used in the laminate analysis when using probabilistic analysis approach. This approach provides means to estimate the significance of incomplete input data as well.

1: Introduction

Tests were conducted for Toray T700 UD epoxy pre-preg laminates in accordance to Federal Aviation Administration (FAA) specified document (Federal Aviation Administration (FAA), Department of Transporation (DOT), Office of Aviation Research (AR), 2001). The reference document (Tomblin, et al., October 2002) used in this work contains 288 pages of test descriptions and test data. Test methods followed ASTM and SACMA standards and appropriate work instructions.

Three batches of material systems were used to define the material baseline properties. Manufacturing (lay-up, vacuum de-bulking, vacuum bag assembly and curing) of the test samples followed the work instructions and processing procedures of the parties involved. The test campaign included the determination of the stiffness, Poisson’s ratio and strength of the material system in its principal directions. Tests were conducted for dry and humidity conditioned laminates at various temperatures. The total number of test samples was 757 and the total number of measurements 981, respectively (see Figure 1:).



a)

	CTD	RTD	ETD	ETW	
X_t	**30**	**18**	**18**	**18**	**84**
E_1_t	16	12	12	12	52
nu_12	16	12	12	12	52
Y_t	**6**	**146**	**18**	**146**	**316**
E_2_t	4	12	12	12	40
X_c	**6**	**18**	**18**	**25**	**67**
E_1_c	2	6	6	6	20
Y_c	**6**	**18**	**18**	**18**	**60**
E_2_c	2	6	6	6	20
S	**6**	**18**	**18**	**18**	**60**
G_12	4	12	12	12	40
ILS		**170**			**170**
				Total, samples	**757**
				Total, measurements	981

b)

Figure 1: Number of various tests conducted shown on the left. Number of samples indicated with bold font. CTD=Cold Temperature Dry, RTD=Room Temperature Dry, ETD=Elevated Temperature Dry, ETW=Elevated Temperature Wet. Typical stress-strain behavior shown on the right in fiber direction (A), transverse direction (B) and in in-plane shear (C). Note that stress scale is 10 times higher in A than in B and C.

The test results provide ply properties that can be used in the design of laminated structures with analytical and numerical simulation approaches. Typically, coupon level tests or sub-element tests are needed for the validation of the design with the final lay-up configuration.

2: Material behavior

Tests were started by the measurements of the physical properties of the constituents and the laminates. This included, for example, uncured fiber areal weight (FAW) and cured neat resin density. The mean value for the FAW deviated only 0.4% from the nominal value of 150g/m2. The coefficient of variation for the FAW was 1.0% and therefore, the amount of reinforcements can be considered to be constant. The fiber density and resin neat density are constant.

The fiber volume content, void content and the cured ply thickness were defined for the laminates. These properties vary more due to the different amount of impregnated resin and bleed.

In linear static analysis the material stiffness in a specific direction is represented with a single value. Carbon fiber reinforced UD laminates have typically 10% higher tensile stiffness than compression stiffness in the ply principal 1-direction. Respectively, typically 10% higher compression stiffness in the transverse direction is obtained when compared to the tensile stiffness. Often, compressive measurements are not carried out in the ply principal 2-direction. In a general case where the loading condition is multi-directional, average moduli are used. Typically the average modulus is stored in the database when measured data exists in both directions. The stiffness of the material is determined from the initial part of the stress-strain-curve. In the reference, moduli were measured between 0.1...0.3% strain levels. Poisson’s ratio can be measured during the tensile test. Quite often this data is missing and an estimate is needed.

Due to the nature of the UD ply (one plane of isotropy) there are five independent engineering constants defining the mechanical behavior of the material. Most often layered laminate structures are simulated with shell elements that consider the out-of-plane shear deformation. Due to the material isotropy, G_{13} equals to the measured G_{12}, but G_{23} needs to be estimated. For solid laminates that are relatively thin, this is not a governing property, however.

The material behavior in principal 1 and 2 directions is very linear and brittle. Instead, the in-plane shear behavior is highly nonlinear above shear strain level of 1%. The ultimate failure strain can be up to 10% (see Figure 1b). An in-plane shear test is typically conducted with cross ply laminates that are rotated by 45 degrees.

Normally, the material failure strength is stored in the material database and the material failure strain is calculated assuming linear association. Stress based failure criteria are used most frequently in the failure analysis. A Linear relation between stresses and strains is a good approximation for direct strains but for shear strains the estimate is very conservative.

Material nonlinearity is considered in advanced, progressive failure based analyses. This topic is currently advancing in the simulation community. For FRPs reinforced with continuous fibers, the assumption for linear material behavior gives solid basis and this approach is used in most applications.

3: Variation

Fiber reinforced composite materials exhibit relatively large variation in their measured properties. Variation is due to, for example, the part manufacturing and testing techniques, ply misalignment and environmental conditions. For cost reasons relatively small sample sizes are used. To obtain reliable design allowables statistical approaches are used.

One basic technique to consider variation is normalization, which is frequently applied to fiber-dominated properties: E_{1t}, E_{2t}, σ_{1t}, σ_{2t}, E_{1c}, E_{2c}, σ_{1c} and σ_{2c}. Test samples have slightly different thickness due to the different amount of resin. The measured values are scaled so that they correspond to the specific fiber volume content.

From the test results the raw data for statistical techniques is obtained. This includes the mean value, standard deviation and coefficient of variation. Distribution types are in some cases reported. Composite properties typically follow normal or Weibull distribution. In general, a coefficient of variation between 4% and 10% is typical for composite materials. Usually mean values are used for stiffness, Poisson’s ratio, and coefficients of thermal and moisture expansion and statistical approach is less important.

A widely-used approach is to determine the strength allowable as a so-called minimum value. It is defined by subtracting from the mean value two times the standard deviation.

In the aerospace industry A-basis and B-basis design allowables are used; A-value: value, above which at least 99% of the population of values is expected to fall, with a confidence level of 95% and B-value: value, above which at least 90% of the population of values is expected to fall, with a confidence level of 95%. A-values are applied to primary structural components where failure would result in a loss of structural integrity. Respectively, B-values are applied to fail safe applications. (Federal Aviation Administration (FAA), Department of Transporation (DOT), 2003)

Using the above statistical techniques different allowables have been derived for the compression strength in the ply principal direction 1 at different conditions. It should be noted that A- and B-basis values have been determined in (Tomblin, et al., October 2002). The results are presented in Figure 2. Also, the amount of samples within +/-25N/mm² around a set of base values was counted to create a cumulated probability density for those ranges and is compared to the values from corresponding normal and Weibull distribution (see Figure 2). The scale and shape parameters for the Weibull distribution were derived from the mean and standard deviation values of the test data as described in (Wallin & Leppänen, 2005).

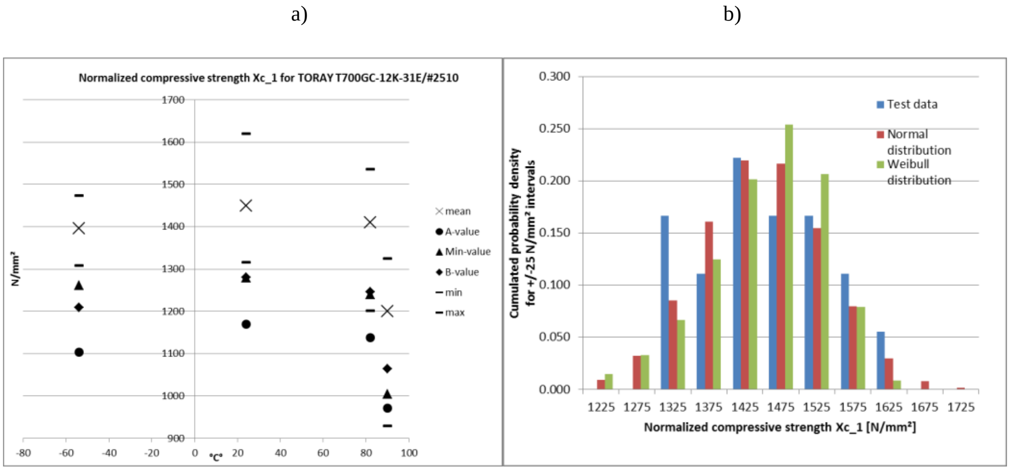


Figure 2: **a) Summary of normalized compressive strength data for the tested Toray T700 UD. The dry and wet data at 82°C has been staggered for clarity. b) Graphical presentation of cumulated probability densities for a range of +/-25 N/mm² around denoted value for RTD.**

For composite material properties one cannot determine definitive trend lines as a function of the fiber volume content. Higher fiber volume content does not automatically lead to higher strength. Instead, high fiber volume content may lead to resin starvation and consequently, larger scatter in the test data. Therefore, strength allowables of the high fiber volume content can be lower than with low fiber volume content. In cases where the coefficients of variation of the pooled data set are higher than 10% or lower than 4%, the reason for the higher or lower coefficient of variation should be investigated before determining design allowable values from the pooled data set (Tomblin, et al., October 2002).

4: Environments

In the aerospace industry materials are tested in addition to RT condition also in extreme conditions, i.e. cold and hot-wet environments. In the reference (Tomblin, et al., October 2002) the material system has been tested at the following environments: CTD (-54˚C, m0.0%), RTD (24˚C, m0.0%), ETD (82˚C, m0.0%) and ETW (82˚C, m1.0%). In reality, the moisture weight content at dry condition varied between 0.2…0.6%, but for simplicity it has been idealized here as 0.0%.

Epoxy resins are known to be sensitive to water, but not for chemicals. Wet conditioned samples were exposed to elevated temperature and humidity conditions as long as the moisture saturation was reached. Additional structural parts necessary for the testing, such as tabs and bond lines, were protected with plastic dipping to retard moisture absorption to unwanted parts.

At high temperatures and high moisture content resin dominated properties degrade. These include the compression strength in the ply principal 1-direction and transverse and in-plane shear properties.

The application may be designed for different environmental conditions than the environments covered in the test campaign. In such situation interpolation may be used to obtain the values at the analysis environment. ESAComp laminate analysis and material database software allows storing material properties at various environments. It provides the same interpolation schemes as described in (Tomblin, et al., October 2002). For example, piece-wise linear interpolation/extrapolation is used in 2D, i.e., when T or m is the same in all input environments. In case of three input environments, equation of plane is formed for interpolation/extrapolation if the plane can be formed from the input points. Moreover, more versatile natural neighbor interpolation (NNI) method is provided when the number of input environments is four or greater. The logic and challenges are illustrated in Figure 3, which also depicts the risk of extrapolation. Clearly, the missing environment is not within the area which could be interpolated with the given data. Extrapolation should be avoided due to unknown drop offs in the material properties.

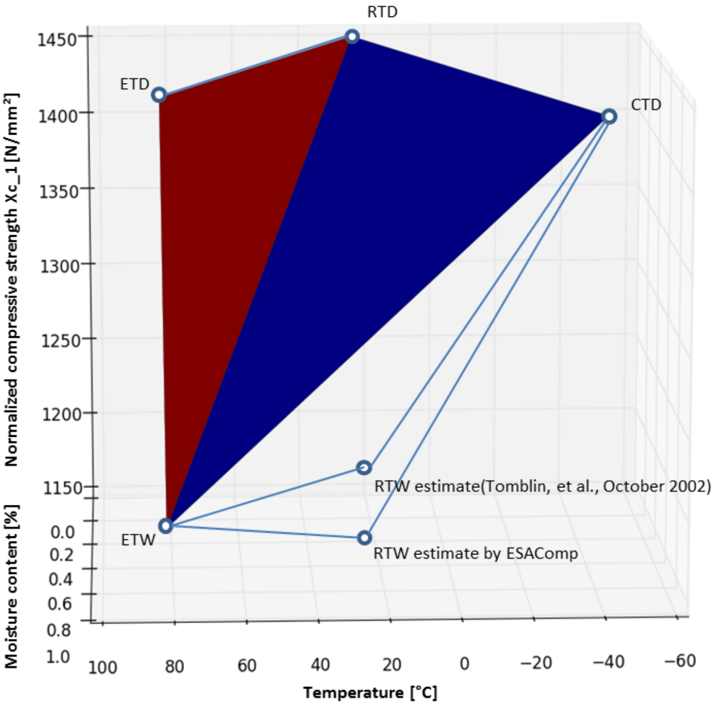


Figure 3: **Normalized compressive strength Xc_1 for different environments. RTW environment is estimate with two different approaches, natural neighbor interpolation and application of the strength increase from ETD to RTD on ETW to obtain RTW.**

5: Probabilistic analysis

ESAComp laminate analysis and material database software allows storing mean values, standard deviations, coefficients of variations and distribution types for independent properties of the material system. Supported material properties are engineering constants, strength values and coefficients of expansion. Distribution types are normal, Weibull, Log-normal and Extreme Value Distribution (EVD). Distribution of material properties can be considered in the various laminate analyses. Moreover, load distributions and variation in layer orientations can be included. In the probabilistic analysis process the same deterministic equations are used as in the normal design (Wallin & Leppänen, 2005). The method is based on the Monte Carlo approach, which is considered as a brute force method. The key point in the analysis is the generation of random uniformly distributed values, which are then transformed to correspond to the specific distribution types of the material. User specified analysis parameters determine how many individual analyses are needed. The following rules are applied during the laminate analysis cycles: 1) in each analysis step new input variables are created for each varied property of the ply material, 2) isotropy (e.g. in 23-plane) is preserved, 3) layers have the same values if they are constructed from the same material, and 4) layer orientations are varied independently.

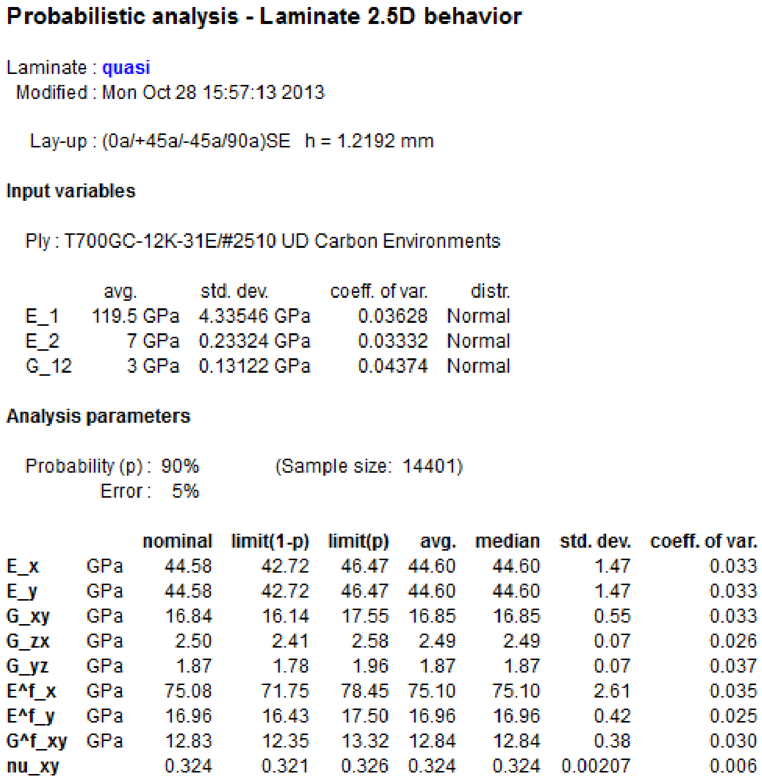
The approach provides a convenient way to investigate the influence of the material variation in the level of the final laminate design. The significance of uncertainties such as missing input data can be predicted by using a guess value and estimate for the scatter. Results of the example study are presented in Figure 4.

6: Conclusions

This work summarizes how the experimental test data for a specific material system is converted to the input data suitable for the simulation of layered laminate structures. Relatively low variance in the material properties reflects the strictly controlled manufacturing and testing procedure as well as the small variance in the properties of the constituent materials. These results should be considered as the highest quality that can be obtained with composites.

The software implementation provides extensive capabilities to store the test data and use it in various types of laminate analysis. ESAComp material Data Bank, which contains 1000+ composite material systems, is frequently updated and the new version includes 51 new reinforced ply definitions (see Figure 5).

Material properties at various environments can also be exported to commercial FE tools, where more detailed analyses can be performed.



Probabilistic analysis - Laminate 2.5D behavior

Laminate : quasi
Modified : Mon Oct 28 15:57:13 2013

Lay-up : (0a/+45a/-45a/90a)SE h = 1.2192 mm

Input variables

Ply : T700GC-12K-31E/#2510 UD Carbon Environments

	avg.	std. dev.	coeff. of var.	distr.
E_1	119.5 GPa	4.33546 GPa	0.03628	Normal
E_2	7 GPa	0.23324 GPa	0.03332	Normal
G_12	3 GPa	0.13122 GPa	0.04374	Normal

Analysis parameters

Probability (p) : 90% (Sample size: 14401)
Error : 5%

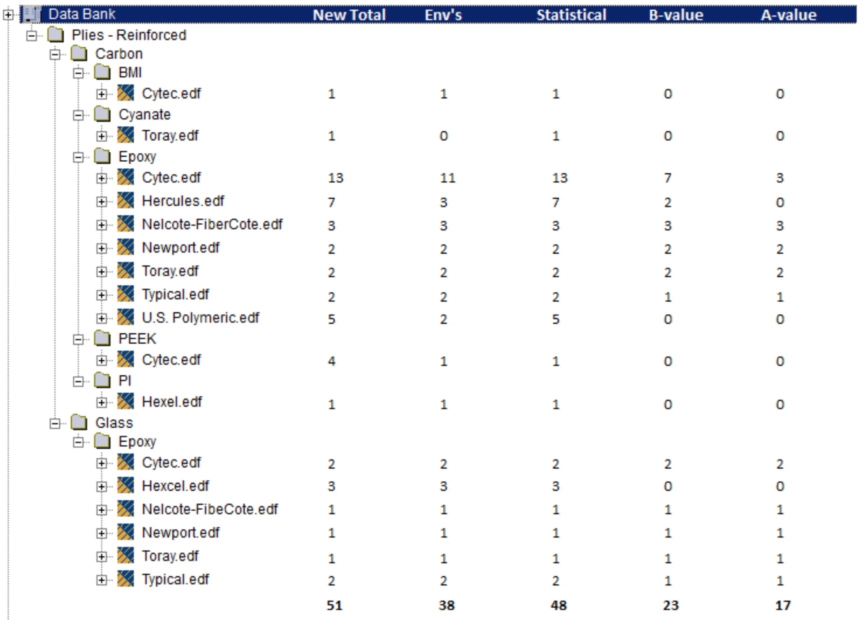
		nominal	**limit(1-p)**	**limit(p)**	**avg.**	**median**	**std. dev.**	**coeff. of var.**
E_x	GPa	44.58	42.72	46.47	44.60	44.60	1.47	0.033
E_y	GPa	44.58	42.72	46.47	44.60	44.60	1.47	0.033
G_xy	GPa	16.84	16.14	17.55	16.85	16.85	0.55	0.033
G_zx	GPa	2.50	2.41	2.58	2.49	2.49	0.07	0.026
G_yz	GPa	1.87	1.78	1.96	1.87	1.87	0.07	0.037
E^f_x	GPa	75.08	71.75	78.45	75.10	75.10	2.61	0.035
E^f_y	GPa	16.96	16.43	17.50	16.96	16.96	0.42	0.025
G^f_xy	GPa	12.83	12.35	13.32	12.84	12.84	0.38	0.030
nu_xy		0.324	0.321	0.326	0.324	0.324	0.00207	0.006

Figure 4: A quasi-isotropic laminate has been constructed from the reference material system. Environment has been set to ETW. Analysis results reveal, for example, that with 90% probability laminate stiffness E_x is over 42.72GPa whereas the nominal value is 44.58GPa.

One important topic that the engineer should keep in mind is that all sources of data contain potential errors. The used reference is of high quality but still includes minor discrepancies.

7: Acknowledgements

The work by Tomblin (Tomblin, et al., October 2002) made it possible to prepare this document and to improve the material Data Bank of ESAComp.



Data Bank	New Total	Env's	Statistical	B-value	A-value
Plies - Reinforced					
Carbon					
BMI					
Cytec.edf	1	1	1	0	0
Cyanate					
Toray.edf	1	0	1	0	0
Epoxy					
Cytec.edf	13	11	13	7	3
Hercules.edf	7	3	7	2	0
Nelcote-FiberCote.edf	3	3	3	3	3
Newport.edf	2	2	2	2	2
Toray.edf	2	2	2	2	2
Typical.edf	2	2	2	1	1
U.S. Polymeric.edf	5	2	5	0	0
PEEK					
Cytec.edf	4	1	1	0	0
PI					
Hexel.edf	1	1	1	0	0
Glass					
Epoxy					
Cytec.edf	2	2	2	2	2
Hexcel.edf	3	3	3	0	0
Nelcote-FibeCote.edf	1	1	1	1	1
Newport.edf	1	1	1	1	1
Toray.edf	1	1	1	1	1
Typical.edf	2	2	2	1	1
	51	**38**	**48**	**23**	**17**

Figure 5: Recently introduced material systems in ESAComp Data Bank. Some of the products may not be commercially available, but the data sets provide valuable information related to properties of different material systems.

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